OMNI SMARTPUMP:
DIRECT CURRENT POWERED DRIP IRRIGATION SYSTEM

FEASIBILITY ANALYSIS AND FINAL EISG REPORT

Prepared For:
California Energy Commission
Energy Innovations Small Grant Program

Prepared By:
Omni Instruments

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ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

FEASIBILITY ANALYSIS REPORT (FAR)

OMNI SMARTPUMP
DIRECT CURRENT POWERED DRIP IRRIGATION SYSTEM

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PIER Subject Area: I/A/W End-Use Efficiency

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LEGAL NOTICE

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which $2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)
    - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html.

Omni Smartpump Direct Current Powered Drip Irrigation System

EISG Grant # 99-12

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Introduction

Current agricultural irrigation methods are energy inefficient. These methods use AC motors ranging from 50 to 80% efficiency to drive water pumps for water spraying or flooding methods that use twice the water needed. Hence moving this volume of water takes twice as much energy as is needed for water-efficient drip irrigation systems. Current drip irrigation systems that use single speed AC motors employ inefficient on/off cycling or complex and inefficient constant pressure plumbing strategies to maintain the required pressure. This project researched the application of high efficiency, variable-speed DC-motor powered water pumps to drip irrigation systems to more efficiently achieve the optimal pressure needed. Such systems promise significant improvements in power use, water use, and labor costs in a wide range of agricultural scenarios.

The project focused primarily on the development of a grid powered, high efficiency, variable-speed DC motor capable of drip irrigating a 2-8 acre area. A secondary objective was to design the DC motor so that it could also be powered by renewable energy sources such as solar panels or wind generators that would charge a battery bank to support intermittent irrigation use. The project identified irrigation pump requirements, purchased compliant 150 GPM commercial centrifugal pumps, and designed and constructed 5 horsepower rare-earth Permanent Magnet Blushless Direct Current (PMBLDC) motors mechanically configured to mate with the pumps. These units were designed and configured to maintain output pressure through a commercial transducer coupled to motor speed control circuitry.

The project assembled and tested four (4) systems. The DC powered drip irrigation systems ran reliably up to 40% of rated power for electro-magnetic and system functional evaluation. At higher power levels, the output switching devices (MOSFET) in the control circuitry failed catastrophically. This failure will require redesign of controller circuitry and incorporation of newer more robust switching devices, which are currently reaching the market. Although testing was stopped by the controller problems, the data generated from laboratory testing below 40% rated power was encouraging.

Objectives

The goal of this project was to determine the feasibility of using a variable speed DC motor in a drip irrigation system to achieve greater energy efficiency. The researcher established the following project objectives:

1. Determine the optimum size of an irrigation area on which to use a drip irrigation system having pressure controlled by a variable speed DC motor.
2. Design a 2 HP DC pump system that can be manufactured for $250 or less.

3. Incorporate into the design the capability to power the DC motor with a photovoltaic or wind turbine system with a battery bank that would sell for under $2,000.
4. Demonstrate reliable operation over the entire range of rated power.
5. Demonstrate a reduction in energy consumption of at least 30% over existing, single speed AC motor-driven drip irrigation systems.

Outcomes

1. The researcher determined a drip irrigation system needed to be capable of supporting an area of 2-8 acres.
2. The researcher concluded a 5 HP DC motor/pump system was needed to irrigate an area up to 8 acres in size. A 5 HP prototype system including the motor, controller and pump was designed, fabricated and tested. The project objective of demonstrating a system with a manufacturing cost of $250 or less was not met since the prototype motor failed above 40% load requiring a redesign. Redesign could impact the system manufacturing cost.
3. To prove this objective the researcher had to show that the DC motor/pump could be produced and sold for $500, and the renewable energy system could be added for less than $1500. Since the researcher was not able to show that the DC motor/pump could be produced and sold for $500, this objective was not met.
4. The output switching devices (MOSFET) in the control circuitry failed when operated above 40% of the rated power.
5. Due to motor controller failure above 40% rated power the prototype system was unable to demonstrate the projected energy savings of 30 to 50%. Below 40% rated power the prototype motor/pump system operated at 70-80% efficiency, which is only marginally better that the 65% to 75% efficiency of the baseline single speed AC motor using on/off operation to maintain pressure.

Conclusions

The researcher failed to prove the feasibility of developing a variable speed 5 HP DC motor/pump system for a drip irrigation application. The limited success of the prototype motor under partial load was encouraging but not sufficient to draw any firm conclusions about the potential for commercial success. Other conclusions are:

1. The researcher’s conclusion that the proposed system would need to be capable of irrigating up to 8 acres was based on the size of a traditional farm plot, availability of appropriately sized 42-volt DC motors, and installation costs. The conclusion appears to be justified and sufficiently supported.
2. The proposed design of the 5 HP DC motor and controller has serious design flaws that cause catastrophic failure of the motor controller above 40% load. The researcher was unable to determine the exact cause of the failure leaving open the possibility that the problem is either centered in the motor controller circuit or is related to an interaction between the new motor design and control circuit. A redesign of the control circuit and possibly the motor design as well will have an unknown impact on the projected cost of the system. As a result, no firm system cost estimate can be made at this time. The researcher believes that recent advances in fuel cell automobile systems will provide the necessary low cost solutions to the technical problems encountered that will eventually allow the system to be manufactured for $250.

3. The researcher's claim that the proposed motor/pump system could be purchased and powered by a small renewable energy system for $2,000 was only partially supported. The PA concurs that a small renewable energy system could be installed for the projected $1,500 cost that would be sufficient to pump 6000 gallons in one hour with a less than 10-foot lift, once a day. However, the projected manufacturing cost of the motor/pump system for $250 with a retail cost of $500 was not supported by the project findings.
4. System reliability is extremely important in any commercial irrigation system. A farmer cannot afford to install an irrigation system that might not sustain his crops. This issue must be addressed before the proposed system can be commercialized.
5. No firm conclusion can be drawn regarding energy savings based on the proposed system design. The researcher claimed some limited energy savings when the prototype motor operated under partial load in a laboratory setting but the type of data collected was not sufficient to support any solid claims in this area. No field-testing was conducted under actual operating conditions.

Benefits to California

It is difficult to quantify the overall beneficial savings without serious market projections, but individual user savings can be quantified and extended into the larger market. A single user would accrue a minimum reduction of 2 kWh/day and a water savings of 6000 gallons, every 2-day watering cycle, which accrues to 180 kWh and 540,000 gallons of water in a 6 month season. A conservative estimate would be 100 kWh and 100,000 gallons per season. This in itself would be of real value and would be compounded if local power generation (solar, wind) were utilized.

On a smaller scale, a farmer may be able to purchase 300 watts of solar panels with batteries for $1500 to $2000 to completely remove this energy load from the grid. That system could generate, store, and apply up to 2 kWh per day of energy to irrigate over 10 acres with no other energy inputs.

In a larger sense, because it removes this energy load from the grid, all Californians benefit when a renewable energy powered water transport system is available to fill the needs of agricultural irrigation and other related water needs.

In addition to irrigation, the pump system developed in this project could fill other needs requiring efficient water movement in areas that have limited grid power availability.

Recommendations

The Program Administrator has determined that the project failed to prove the feasibility of using high-efficiency DC motors for driving drip irrigation pumps to reduce electricity use in agricultural applications. The fact that the prototype system was able to operate efficiently up to 40% rated power is encouraging but insufficient to establish technical or commercial feasibility. The PA recommends that any future R&D development of this concept be contingent upon addressing the following concerns:

- Identify the exact cause of failure above 40% load and redesign the motor controller and motor, if necessary.
- Show evidence of a clear market connection by teaming with a motor/pump manufacturer.

- Substantiate the energy savings of the variable speed DC motor over existing variable speed AC motors that could be adapted to drip irrigation systems.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market

The researcher has held informal conversations with individuals/users who have indicated interest, but there is no documented marketing plan in place to take the unit to the wholesale market. IPT (A manufacturer of pumps), Transmagnetics Inc., and smaller community-based agricultural suppliers have indicated interest in this project. The researcher needs to draft an initial business plan.

Engineering/Technical

The researcher failed to establish technical feasibility of the proposed motor/pump system in a drip irrigation application. The limited technical success of the motor/pump system when operated under 40% power is sufficiently encouraging to warrant continued development of the motor and controller. The researcher's assertion that new, high power MOSFET devices that are just being made available on the market will solve all of the technical problems in the design is not substantiated.

Legal/Contractual

No patents have been applied for related to the motor or motor controller design. Given the remaining design flaws that still need to be worked out a patent application at this point in time would be premature.

Quality Plans

Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, Product Safety, and Environmental Impact plan. The researcher has not reported the completion of any of the above plans. When the researcher has finalized the system design and has teamed with a manufacturer the applicable Quality plans will need to be drafted.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere

Production Readiness/Commercialization

The researcher notes, and the PA concurs, that unit redesign for manufacturability is needed. Further, efforts to identify a commercializing partner must be initiated and concluded.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from the successful conclusion of this research is the increased affordability of electricity in California. This will come about through the reduced demand for electricity to pump water for agricultural irrigation. Industry, agriculture, and wastewater treatment are the largest users of electricity in California, consuming about one third of the total. As the end user of the water, the drip irrigation system requires only half as much water; hence the electricity used to supply irrigation water to that parcel of land is halved. Also, the inherent efficiency of the DC motor used saves additional electricity at the point of use. Finally, if the drip irrigation system is configured to operate on renewable energy sources, the point-of-use demand for grid supplied power could be completely eliminated, benefiting all ratepayers in the market by increasing the reserve margin of generation and thus reducing the price.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

DIRECT CURRENT POWERED DRIP IRRIGATION SYSTEM (SMARTPUMP)

EISG AWARDEE
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Legal Notice

Inquires related to this final report should be directed to the Awardees (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Acknowledgement Page

Bryan Cooper – for Management and Administrative Persistence
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Abstract

The purpose of this project is to define and examine the use of low cost, high efficiency 42 Volt pressure regulated output water pumping system (SmartPump) for farm scale drip irrigation. Such systems promise dramatic improvements in power use, water use and labor costs in a wide range of agricultural scenarios.
Project focused on a 2-8 acre irrigation scenario with solar panel, wind or low power battery recharging in the field. Hardware to be used was a new design 5 horsepower rare-earth Permanent Magnet BrushLess Direct Current (PMBLDC) motor mechanically configured to mate with a 150 GPM commercial centrifugal pump. Output pressure is maintained through a commercial transducer coupled to motor speed control circuitry. Four (4) systems were mechanically built and testing begun. Systems have been run reliably at 40% of rated power for electro-magnetic and system functional evaluation. Anomalies of switching devices and control circuitry have prevented full power evaluation and will require redesign of controller circuitry with incorporation of newer switching devices. Field-testing was not accomplished due to the controller problems but the experience with low power operation indicates basic system stability suitable for field applications.
With the difficulties in control circuitry resolved this design can be committed to production and deployed both in California and elsewhere to economically halve power and water requirements in small and medium scale agriculture.

Executive Summary

Introduction:

Current irrigation practices are dramatically inefficient for the following reasons:

1. Basic Alternating Current (AC) motors used in agriculture are fundamentally inefficient ranging from below 50% to 75% with federal mandates to 80% in process. Maximum theoretical efficiency of AC motors is approximately 85% due to the need to supply the energy required to provide reactive magnetic fields for electro-magnetic motor action.
2. AC motors are cumbersome to control due to the requirement for changing the frequency of the power source to vary speed. The frequency change invariably causes a 10% loss in energy as a burden and adds weight, volume and cost to the system.
3. In the case of constant pressure requirement for drip systems drive systems must be pressure controlled or onerous constant pressure plumbing systems must be employed to throttle water pressure and pump motor duty cycle to maintain appropriate emitter pressures. This causes lower system efficiency, higher capital cost and an inflexibility of use, which translates into less efficient application practices due to high setup costs.
4. AC power lines to motor/pump installations is generally inefficient due to location and duty-cycle issues and can amount to losses of over 10% and high capital costs for custom power lines and power delivery services.
5. Irrigation in spray form or flooded field requires twice as much water as do drip irrigation systems. Losses are in the form of evaporation and runoff plus the added burden of weed growth and it's transpiration.
6. Irrigation in drip form reduces saltation and mineral leeching due to selective and accurate application. Water-soluble amendments can be inserted at the output head of the pump and be accurately applied as an added benefit.
7. Peripheral agricultural land often occurs in geography where conventional irrigation systems re challenged regarding power, water or farmer accessibility

Project Objectives:

To prototype and evaluate a system that can meet the needs of the drip irrigator and to extract data to confirm the efficacy of production, distribution and application of such a system. Details of that process are:

1. Research and discovery of optimum scale for end use.
2. Define system architecture
3. Research and discover suitable pump vendor
4. Research and design magnetic structure
5. Research components and design controller
6. Define mechanical aspects and document
7. Define controller and alternate circuitry.
8. Purchase/fabricate components
9. Assemble and preliminary test of controllers

10. Assemble motor components
11. Assemble motor-pump systems
12. Bench test and evaluate systems
13. Full test and evaluate systems
14. Field test systems

The project outcomes:

1. Local and UC experts were consulted to discover optimum scale for SmartPump.
2. System architecture was defined by scale of requirement.
3. Pump vendors for rotary pumps were researched and the optimum vendor selected.
4. Magnetic structure was designed using available laminations and magnets with a MathCad based formula.
5. Controller's engines were selected from available vendors with appropriate performance aspects and were mated with appropriate MOSFET switches.
6. Mechanical aspects were derived from available components and documented.
7. Printed circuits were laid out on a commercial layout program.
8. Components were purchased or fabricated from conventional and local sources.
9. Assembled and tested controllers under low power conditions.
10. Controllers and magnetic components assembled to mountings.
11. Assembled SmartPump systems.
12. Bench tested units under low load conditions.
13. Began full test of systems and discovered cataclysmic power sensitivities.
14. Field test not accomplished due to power sensitivities.

Conclusions:

1. Current technology is able to produce cost-effective systems that reduce power consumption by 30 to 50% for 42 Volt powered drip irrigation systems.

2. Water use in drip systems such as these is half that of flooded or sprayed agricultural irrigation and lower use contributes to additional power savings in pumping.

3. Use of pressure transducer speed control offers unparalleled flexibility in system setup providing additional cost benefits.

4. Appropriate control components are rapidly becoming available due to the stimulus of 42 Volt automotive systems becoming standardized in the next two years. Current devices under evaluation for MOSFET switching will be a commodity by the year 2005, control integrated circuits will plummet in cost and magnet cost will also be reduced by half reducing all reducing Original Equipment Manufacturer cost to below $250 and hence affordable to Californian agriculturists

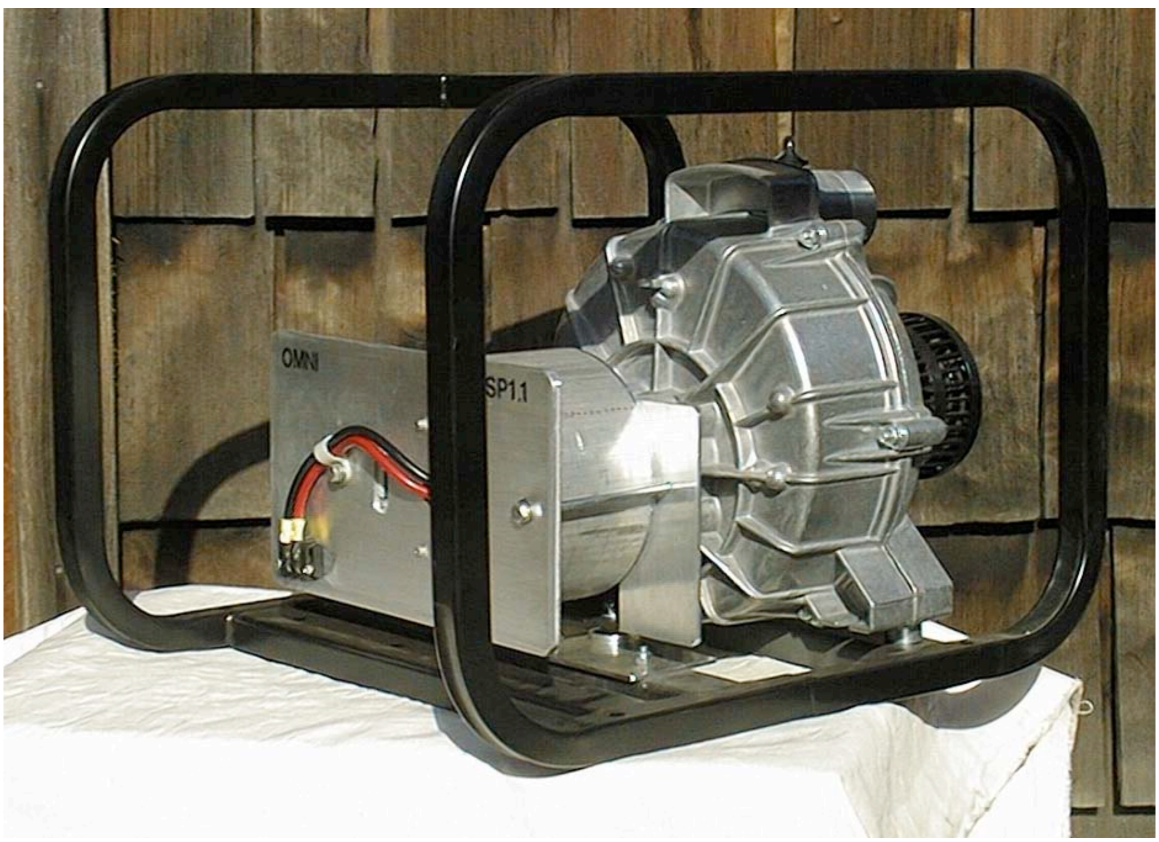
5. There is significant OEM interest in producing such a product. Pump manufacturers may incorporate motors into their products as easily as they currently incorporate gasoline engines.

Recommendations:

Controller requires production redesign with currently available high power MOSFET power switches while concurrently discussing production with several pump manufacturers.

Public Benefits to California:

All Californians stand to gain from incorporation of SmartPump systems into our agricultural environment where we would gain through power consumption reductions, water conservation improvements, soil conservation improvements and reduced effluent discharge relative to gasoline or diesel pumping. Increased farm productivity is an added byproduct of SmartPump use.



Introduction:

Electric motor design is still in a "black art" category over 100 years after Tesla contrived the Alternating Current (AC) motor and the Brushed Direct Current (BDC) motors were commonplace in our transportation, factories and agriculture.
Agricultural irrigation has also been subject to rules of physics and convenience aspects for many years. California has employed AC motors to lift water into aqueducts and out to crops for the same hundred years – water has been available and power has been cheap.
In these times, cost of power has increased dramatically and water is less plentiful. Populations are changing and labor costs have increased significantly as California's demography shifts from farm economy towards technology and service as the population doubles over a 20year period.
With these shifts in mind, and the water situation in the world accelerating towards commodification, water use and associated energy costs comprise a critical target for action to avoid serious crisis in this coming decade.

Project Objectives

1. Determine optimum sizing and operational parameters for typical drip irrigation scenario
2. Define system architecture meet sizing requirements for power, pressure and flow
3. Determine a pump vendor and specific pump for the project
4. Determine magnetic structure to match pump's speed and torque requirements
5. Design 2 motor controllers from reference information and electromagnetic requirements
6. Define overall mechanical characteristics and document
7. Layout printed circuit boards for 2 controllers using layout program
8. Purchase/Fabricate components
9. Assemble and preliminary tests of primary controller
10. Assemble motor components
11. Assemble motor-pump systems
12. Verify/Bench Test systems
13. Verify full performance in test cell
14. Evaluate systems performance in the field
15. Report

Project Approach

Project approach was for the primary researcher to go into the field and research the actual requirements through UC Extension agriculturists, local college agronomists, college biologists, vintners and horticulturists. This information was augmented by pump and controller research to fill out the basic data needed. Having the basic requirements in line the conversion to specification mathematics were accomplished and converted into system specifications for design of the SmartPump.

With specifications in hand the actual components were specified and the system/controller were designed and committed to purchase and fabrication for system construction. On receiving components, contract technicians performed the majority of the assembly of the components and system.

Test fixture construction and testing were performed by the principal investigator and consisted of 5 stages. First was an assembly test to verify assembly where any errors in layout authorship would come to fore. Several errors were discovered due to photolithographic incompatibilities and were easily repaired.

Second test level was a power on, resistive load startup test to determine functional fitness. This test was successful for 3 of four units.

The third test was a bench test with a specially constructed test motor and examined startup and throttling to RPM with nominal loading. Waveforms were examined for conformance to expectations and margins of safety. Three (3) controllers passed test after adjustment of two capacitor values to provide adequate current limiting margin and response.

The fourth test series was in the first pump system with no load and no transducer attached (manually throttled). Three controllers passed this test.

The fifth and final test series was in the units under full operating conditions and loads. Difficulties at this level appeared as failures in switches at load conditions passed 40% of full loads (30-40 Amperes) and the bulk of the ongoing efforts were in discovering causes for the failures and appropriate changes to allow controllers to meet specification without catastrophic failure.

Project Outcomes

1. The irrigation scale for end use was researched through local vineyards and UC extension agent and it was discovered that delivery of 100 to 150 GPM at 30PSI would satisfy a 1 to 2 hour soak period on 2 to 8 acres for typical vineyard and orchard situations. A working equation was evolved for water needs and pipe sizing.
2. The nature of the varying water source quality and power required to perform to the basic specification dictated a modestly high speed rotary "trash" pump and a 3600 RPM motor capable of providing 5 horsepower at that speed. Pressure control is defined by an external pressure sensor strategically located with cable connection to signal conditioning integral to motor controller. Motor controller containment within the motor case was selected to reduce Radio Frequency Emissions, reduce parasitic inductances, and decrease mechanical component count to manage moisture and thermal issues more effectively. Rotor position sensing for commutation data is done by a sensorless technique that relies on the voltage generated by the rotation of the magnetic rotor.
3. Evaluated 5 vendors and selected IPT pumps for their graded 150 GPM pump bodies that cost less than $100 each in OEM quantities. IPT also manufactures enclosures appropriate to the system specification.
4. Magnetic structure was analyzed and conventional (commercially available) alternator laminations selected and sized for the 100 Ampere/42 Volt flux range

stator and the rotor defined by the stator characteristics to 12 pole/24 magnet commercial 1 Tesla NdFeB plated magnets.

5. Controllers selected were 1. Micro Linear ML4428, a sensorless phaselock commutation device, for primary/short development cycle and 2. Analog Devices Digital Signal Processing (DSP) motor controller family as longer development cycle backup. MOSFET switches were selected as the strongest commercial devices available in TO-247 packaging (STW80N06 – 80Amperes continuous/60 Volts/ .008 Ohms).
6. Mechanical design was defined by pump dimensions, motor configuration and mounting cage characteristics. The rugged cage selected serves as a strong foundation and protection for the system for transport or regular use.
7. Primary controller was designed from reference designs and configured with a MathCad based formulaic solver from the component vendor, Micro Linear. Layout was circular to conform to the motor enclosure packaging. Secondary controller was designed from reference designs and configured to act as an in-circuit development platform. Printed circuit layout was performed using a commercial printed circuit designer program.
8. Components were purchased and fabricated during a 5month period with nominal lead times. Schedule time was 90 days.
9. Primary controllers were assembled and tested using modest resistive test loads to check for proper logical and functional operation. 3 passed the tests with minor changes in component values. Further testing with a test motor with similar magnetic characteristics uncovered 2 current-limit timing issues (over-current delay response and current sense response) that were brought into specification by changing capacitor values. Controller-motor combination delivered classical current-limited response at low speeds and near sinusoidal response at high speeds; all at light loading (~5 amperes).
10. Motor stator was hand wound and tested for field consistency. NdFeB magnets bonded to rotor and rotor was balanced and tested for bonding strength and magnetic field consistency.
11. Two (2) motor/pump assemblies completed to test-ready status and 2 ready for final assembly.
12. Bench test begun and completed satisfactorily at low power using manual throttle control.
13. System evaluation begun but stalled due to catastrophic MOSFET switch failures at modest current levels. Difficulties are primarily in MOSFET output switches, particularly the intrinsic diode that recovers catastrophically at high current in conjunction with low inductance stators. This difficulty is very difficult to discern as the failure modality is very high current, very short (100 nanoseconds) pulses, which generate high dv/dt events through interaction with parasitic inductive elements. The failures are catastrophic and present as smoke and shorted MOSFET devices. Events are difficult to isolate and capture to allow full analysis due to their somewhat stochastic moments of occurrence. Discussions with

manufacturers of the devices validated the theorem but offered little relief with the high performance magnetic configuration that must be mated to electronically. Newer devices designed to control 42 Volt automotive systems managing several hundred amperes and packaged with much lower parasitic reactance will provide a certain solution to the problem. An appropriate device from IXYS semiconductor is now being evaluated and several other manufacturers are about to release equivalent devices. System efficiencies were not fully obtainable due to lack of performance at projected power levels though nominal tests at 30% power displayed motor-pump efficiencies of 70 to 80% based on flow rate. These measures are not accurate and were used to determine thermal/power margins as an analysis/troubleshooting routine.

14. Field tests were not performed due to unavailability of full performance systems

Conclusions

1. This project has advanced understanding regarding MOSFET switches to commutate NdFeB based motors in the low voltage, multiple horsepower range. Small transport systems will rely on this combination in stand-alone or hybrid configuration in material and people movers.
2. Overall SmartPump system design evolved simply and is a good example of form-follows-function.
3. Project goals were overly ambitious for the funding and time available.
4. Rare-earth magnet performance is essential for motor efficiencies over 85% and the pricing for such components has fallen by a factor of 2 in the last 24 months indicating a mature, commodity product that enables compact, inexpensive motors. Several similar configuration NdFeB motors have appeared on the transportation market and all claim efficiencies exceeding 90%.
5. Power MOSFET technology has evolved during the grant period and now can reliably support multiple horsepower motor commutation at modest costs. This is largely due to the move towards 42 Volt automotive systems combining alternator and starter/auxiliary propulsion.

Recommendations

It can be shown that SmartPump is an enabling technology that is ready for commercialization. Several pump manufacturers dsplayed interest in the technology without prototypes available, but none would risk time or capital in an area they did not feel comfortable in. This is a new technology application for capital equipment manufacturers that must be presented in a near final form to coax them in to taking a risk on a “new” product. To accomplish this requires effort on the controller to bring it to a reliable, commodity status by focused design effort relying on newer components and packaging technology..

Public Benefits to California

It is difficult to quantify the overall beneficial savings without serious market projections, but individual users can be savings quantified and that extended into the larger market. A single user would accrue a minimum reduction of 2 KWH/day and a water savings of 6000 gallons, both on every other day, which accrues to 200KWH and 600,000 gallons of water in a 6month season. A conservative estimate would be 100KWH and 100,000 gallons per season in itself would be of real value and would be compounded if local power generation (Solar, Wind) were factored into the equation and if a larger service area was serviced via plumbing. System installation costs are also a source of indirect benefit to Californians at large.

To personalize the potential costs and benefits, $1500 purchases 300 watts of solar panels with batteries which generate, store and apply 2 KWH per day of energy to irrigate over 10 acres with no other external inputs. Wind energy can be applied for less than $1000.

In a larger sense all Californians benefit when a renewable powered water transport system is available to fill the needs of agricultural and other water users.

In addition to irrigation, SmartPump can fill other needs that require efficient water motion away from normal power sources.

One requirement is a small city sewage reclamation system where water is to be dispersed to evaporation areas that are distant from power mains. Conventional pumps are vulnerable to high humidity conditions and expensive to acquire and operate..

Possible savings are being examined by this city in installation, capitalization, operation and public visibility.

Another need is a quiet propulsion unit for shallow water navigation. Using SmartPump allows minimum draft and simple installation and convenient power management with conventional batteries and solar cells or other source of modest power.

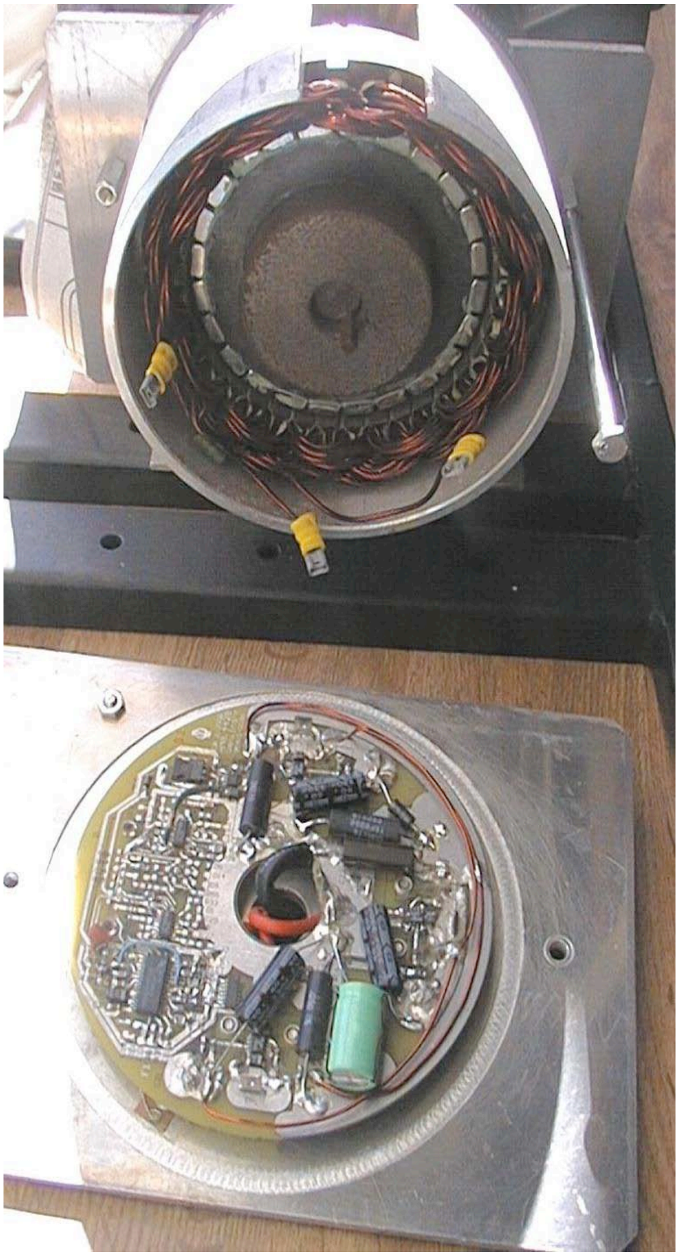
Development Stage Assessment

Development Assessment Matrix

Omni SmartPump

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

- Marketing – Informal marketing resulted from interactions with agriculturists and pump manufacturers enough to indicate clear interest. This interest has been strengthened and validated by further communications with potential users who are seeking solutions for off-grid or remote water management. Additional markets such as electric boat propulsion, forest restoration, firefighting and wastewater management will reduce production costs locally and the foreign market will provide local employment
- Engineering/Technical – Feasibility has been demonstrated and product development has begun. Newer MOSFET devices allow basic design to be updated to the higher power components in a direct way to take advantage of work previously completed.
- Legal / Contractual – Due to the nature and application of the technology, patent rights are appropriate only to protect the final product. Safety/liability issues are easily bondable with the automotive sector providing legal precedents in this class of systems.
- Risk Assessment / Quality Plans – Quality presence has not been heavily researched as the nature of the product makes it inherently fit for it’s purpose.
- Strategic – Several strategies have been superficially examined (licensing, contracting, franchising) and some combination must be defined in order to provide distribution and availability for California users.
- Production Readiness – Requires production design with accent on manufacturability.
- Public Benefits / Costs – Benefits may be realized by early availability through strategic production and marketing through farming organizations.



SmartPump Motor/Controller

Alternator Stator laminations Wound and terminated with Automotive “quick disconnect” terminals.

NdFeB (Neo) magnets epoxied to gear-blank rotor

Controller Printed Circuit Assembly with Surface Mount Components

TO-247 packaged MOSFETs mounted under board to heat sink panel